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P R O C E E D I N G S

O F T H E

1964 ARMY SCIENCE CONFERENCE

UNITED STATES MILITARY ACADEMY, WEST POINT, N. Y.

17-19 JUNE 1964

V O L U M E   I

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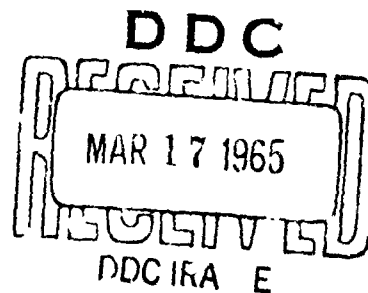
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SUPERCONDUCTORS IN ADVANCED ELECTRONICS

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1. INTRODUCTION

A superconductor is completely free of ohmic losses for a
direct current and nearly free of such losses for alternating
currents with frequencies up to Mc/sec and higher, depending on the
circumstances. Circuits with superconducting inductors and
capacitors, and superconducting interference shields for such
circuits thus appear as a natural choice where a minimum of loss,
noise, and interference from the environment is desired, as for
example in the first stage of a communications receiver. Super-
conducting resonant circuits with very high Q values (10^6 and higher)
have indeed been successfully operated in the Mc/sec range (1), (2),
but the tuning of such circuits proved to be difficult. It was
recognized at USAELRDL (3) that remotely controlled switches would
solve the tuning problem provided the switches would introduce no
loss into the circuit. The "cryotron," a superconducting computer
element (4), has often been called a superconducting "switch," but
it is really only a current gate with zero resistance in the "closed"
position and a finite resistance--a few hundred ohms at most--in the
"open" position. A superconducting switch with a true "open"
position (virtually infinite resistance) was, however, deemed
necessary for tuning and, in fact, for most purposes. It was
predicted (5) that a novel combination of superconducting solenoids
with superconducting contacts would constitute a remotely controlled
superconducting switch with the desired properties. Experimental
work was begun in fall 1963 which soon resulted in the construction
of an actuating mechanism capable of giving contact forces up to
1000 g (Section 2). The search for a suitable superconducting
contact material and a suitable contact configuration proved much
more difficult, but contacts which would reproducibly control super-
currents of 16 A had been developed in spring 1964 (Section 3).
This surprisingly high current value permits the use of the new
relay switch not only for the low power applications mentioned in
the beginning but also for high power applications, especially in

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connection with the now widely used superconducting solenoids for the
generation of high magnetic fields. Using the analogy between a
hypothetical lossless capacitor and a superconducting inductor or
solenoid, basic circuits for the "charging" and "discharging" of a
superconducting solenoid were developed (6) and some of them tested
(Section 4).

The low operating temperatures of the presently used super-
conductors often prevent the application of superconducting devices
and circuits in spite of their obvious advantages. Recent progress
in this area as a result of simplified cooling methods and of im-
proved materials is outlined in Section 5.

2. RELAY MECHANISM WITH SUPERCONDUCTING COILS

The mutual attraction and repulsion of two similar super-
conducting coils were used to actuate the first experimental relay
switch built by the authors, shown in Fig. 1. Other possible magnet
configurations have been discussed elsewhere (5). No soft iron
return path was used for the magnetic flux, because this would in-
crease the cooling requirements for the relay, and also because the
high magnetic fields generated by superconducting coils tend to
magnetically saturate the iron, thus making it useless.

Each magnet coil was made by winding approximately 1300
turns of molybdenum-rhenium wire on a nylon bobbin with 1.6 cm outer
diameter. Molybdenum-rhenium is a "hard" superconductor, that is,
a material remaining superconducting in a strong magnetic field and
when carrying a large current.

The relay consists of two simple bakelite parts, one
stationary and one movable, each carrying one coil and one contact,
(Fig. 1). The magnetic force, magnified by lever action, acts on the
two contacts. To measure the contact force, as a function of coil
current, a nylon string was attached to the upper contact and
connected to a balance on top of the cryostat in which the relay was
kept at the temperature of $4.2°K$. Some of the results are given in
Table II, Section 3. The force increases strongly with the coil
current and reaches ≈ 1000 g for the maximum current carrying
capacity of the coils (≈ 6.4 A). A conventional copper wire of equal
thickness (0.25 mm) in place of the Mo-Re wire would sustain no more
than ≈ 0.1 A. It is this difference in operating current for a given
winding which makes superconducting coils so superior to conventional
ones in producing mechanical forces for the operation of contacts and
other purposes.

3. CONTACTS FOR LARGE SUPERCURRENTS

In 1914 Kammerlingh-Onnes, the discover of superconductivi-
ty, made the first superconducting "switch" when he pressed two

pieces of superconducting lead together and found superconductivity
across the contact (7). Later workers found that an oxide layer and
even an insulating layer of moderate thickness (up to 10^{-7} cm)
between the contact surfaces does not prevent superconductivity across
the contact (7),(8). This surprising effect was explained theoreti-
cally only recently by Josephson (9)("Josephson-Tunneling").

When the current through a superconducting switch is raised,
a critical current value, I_{cr}, is finally reached at which the super-
conductivity across the contacts vanishes. This becomes evident as
a voltage across the contacts. I_{cr} can be determined by observing
this voltage with separate voltage leads, as shown in Fig. 1. All
the switches reported in the literature had small I_{cr} values, usually
much less than 1 A. Various contact pairs used in the initial phase
of this work were found superconducting, but with disappointingly
small I_{cr}. Results for three typical contact pairs are listed in
Table I.

TABLE I

contact 1	contact 2	contact force (g)	I_{cr} (A)
multifinger arrangement	Nb - sheet	650	$2 \cdot 10^{-4}$
of Nb wire (0.4 mm)		750	$2 \cdot 10^{-4}$
Pb-Sn alloy (40/60), ball shaped	Nb - sheet	350	$2 \cdot 10^{-3}$
		400	$11 \cdot 10^{-3}$
		550	$73 \cdot 10^{-3}$
		800	$74 \cdot 10^{-3}$
Pb-Sn alloy (40/60), ball shaped	Pb-Sn alloy (40/60) ball shaped	550	$18 \cdot 10^{-3}$
		850	$18.5 \cdot 10^{-3}$

It was deduced from these data that (a) increasing the contact force
beyond ≈ 500 g gives little improvement, and that (b) at least one of
the contacts should be of a soft material, such as the lead-tin alloy
used in two of the experiments. It is known, however, that even this
alloy becomes rather hard when cooled to liquid helium temperature.
Pure lead was chosen therefore for the next experiments. Lead re-
tains a plasticity at $4°$K comparable to that of copper at room
temperature. The plasticity of a contact material appears to secure
the formation of an "effective" contact area larger than that
obtainable with a hard material (7). The contacts finally used in
this work were of lead galvanically coated with a very thin layer of
tin. The contacts were kept under helium gas during the cooling
down period. These measures were aimed at preventing the formation

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of layers of oxide, ice, or frozen air on the contact surfaces. The results with tin coated lead were excellent and vastly superior to any previous results, as shown in Table II. This table also gives the contact force as a function of coil current.

TABLE II

coil current (A)	contact force (g)	I_{cr} (A)
1.5	350	< 1
2.3	475	2.3
3	600	13
4	800	13.5

These results were quite reproducible. In one run an I_{cr} value of 16 A was attained. Technical refinements of the crude experimental set up, shown in Fig. 1, will undoubtedly improve the performance of the superconducting relay switch further.

4. APPLICATIONS

The successful operation of radio frequency and of microwave circuits made of superconducting components has been reported by other groups (1),(2),(10). The new superconducting relay switch described in the previous section now makes possible the tuning of such circuits by remote control. Several switches could serve, for example, to add capacitors or inductors to a superconducting, high Q resonant circuit. Since the switches have zero resistance in their "closed," and virtually infinite resistance in their "open" position, the switches will not introduce any losses into the circuit (3). An older switching device, the "cryotron," could not be used for this purpose, because it has no true "open" position, as discussed in Section 1.

The first step toward high power applications of the new superconducting switch was taken by the authors when they connected the new switch to the terminals of a high field (42 kOe) superconducting solenoid, and used it to control the solenoid current. The solenoid is of medium size (1.25 cm bore) and has an inductance of ≈ 5 Henry. The highest supercurrent which could be controlled so far was 12 A. One purpose of these experiments is to explore the storage of electrical energy with the solenoid. The storage of electrical energy in low loss capacitors has been used in electronics for many years for the operation of pulsed transmitters, of pulsed light sources, and also in plasma research. A superconducting solenoid can be considered as an inductor which is lossless in low frequency applications. The properties of such an inductor are set in analogy to those of a hypothetical leakage free capacitor in Fig. 2. The quantum of charge for the capacitor is of course e, the electronic

charge; its equivalent for the inductor is the newly discovered (11) quantum of magnetic flux, hc/2e (h: Planck's constant, c: velocity of light). Since both "charge quanta" are very small, they are not observed except under very special conditions and the charging processes can be treated as continuous in the following. Charging the capacitor is accomplished through the transfer of electric charge between the capacitor plates, resulting in a voltage between the plates. "Charging" the inductor is accomplished by building up a current through the winding, resulting in a magnetic flux threading the hole of the inductor. The charged state of the capacitor is characterized by an open circuit, the analogous state of the inductor by a short circuit (produced by the closing of a superconducting switch). The maximum charge of the capacitor is limited by dielectric breakdown, the maximum magnetic flux of the inductor is limited by the field induced breakdown of the superconductivity of the winding. Technically attainable values for either kind of breakdown are used in Fig. 2 to demonstrate that the energy, w, which may be stored per unit volume of the device is much greater in the case of the solenoid. Formulas for the total amounts of energy, W, storable in either case are also given in Fig. 2. The largest superconducting solenoids which are now commercially available have bores greater than 15 cm and inductances up to 1000 Henry. Carrying a typical current $I \approx 20$ A, such a solenoid stores $W \approx 2 \cdot 10^5$ Joule. The corresponding value for a capacitor of comparable size and weight would be much smaller.

The bottom part of Fig. 2 illustrates the transfer of the stored energy into an outside load R'. For the capacitor, this is accomplished by closing a switch, for the inductor by opening a superconducting switch. Until now, only thermally activated cryotrons were used in connection with superconducting solenoids. The resistance of a "thermal" cryotron can be varied only slowly (within ≈ 20 sec) from zero to the maximum value of a few ohms. Most of the stored energy is thus consumed by the cryotron itself and transfer to an outside load is ineffective. The discharge process presented in the right bottom part of Fig. 2 is possible only with a superconducting switch which goes from "zero" to "infinite" resistance immediately, such as the relay switch built and used by the authors.

Figure 3 shows the two analogous basic charging circuits for alternating current. The timing for the periods of charging is indicated. The superconducting switch across the inductor is open only during the charging period. When it is closed, no voltage is applied to the inductor and its current not influenced by the power source. The charging is completed when the supercurrent through the inductor equals the peak current of the power source.

Figure 4 shows two circuits employing current transformers. One winding of a current transformer is outside of the cryostat. The energy transfer is through the wall of the cryostat by induction. This is superior to the direct transfer of energy through

heavy current leads which are difficult to cool. Except for the
current transformer, the first circuit in Fig. 4 operates like that
in Fig. 3. The second circuit in Fig. 4 is analogous to a vibrator
circuit with capacitors. It converts the stored direct current into
alternating current by using a reversal switch S2, and by inter-
mediately storing energy in the superconducting transformer winding
W2 combined with the closed superconducting switch S3. The timing
of the switches for discharge is indicated. With different timing,
the same circuit is used for charging.

Figure 5 indicates the storage of energy in a superconducting
combination S and L as before, but a switching transistor T 1 outside
of the cryostat is connected parallel to S. In the "standby" position,
S is opened and the solenoid current is forced to flow through T 1.
The storage is then of course no longer loss free, but the loss during
a short standby period is tolerable. For operation, the switching
transistors T1 and T2 are alternatingly opened and closed with the
resonance frequency of the transmitting circuit, thus converting the
stored energy into a very powerful radio frequency signal.

The equations at the bottom of Fig. 2 indicate that a
"discharging" inductor behaves essentially like a constant current
generator. This feature, together with others listed above, makes
a superconducting solenoid combined with a superconducting switch
particularly attractive for the operation of pulsed light sources.
At the onset of the pulse the resistance of such a device is usually
high; the solenoid then applies a high "igniting" voltage. Later on,
when the resistance of the device drops, the voltage drops according-
ly, and the initial current is never exceeded. This is in contrast
to the action of a capacitor--essentially a constant voltage genera-
tor--which tends to apply too much voltage after "ignition," so that
much of the pulse energy must be destroyed in a stabilizing resistor
or the like. Superconducting solenoids and relay switches capable
of delivering pulses of several hundred volts and many thousands of
Joules should be obtainable. Fig. 6 shows a simple circuit for
pulsed light sources, based on principles similar to those of Fig. 5.

COOLING PROBLEMS

In the usual laboratory operation of a superconducting
circuit the circuit is housed in a cryostat which is cooled by
transferring liquid nitrogen and liquid helium into appropriate
compartments of the cryostat. The transfer of a cryogenic liquid is
a difficult and time consuming manipulation which is necessary be-
cause the consumer of the cooling energy, the circuit, is separated
from the source of the cooling energy, namely the liquefier for the
helium or nitrogen. In this fashion several cryostats can be served
from one liquefier, permitting simultaneous work on several experi-
ments. The laboratory method of cooling, however, is neither
necessary nor even suitable in the technical application of

superconducting circuits. Here, the best approach is obviously
through a combination of the cryostat with the liquefier (or another
source of cooling energy), such that fully automatic operation with-
out any external transfer of cryogenic liquids is accomplished.
Refrigerators of this advanced kind, called "closed cycle refrigera-
tors" are now commercially available in various sizes, even rather
small ones. A closed cycle refrigerator has several "cooling stations",
essentially cooled metal plates. The superconducting circuit is
mounted of course at the station with the lowest temperature.
Electrical leads, coaxial cables, and waveguides connected to the
superconducting circuit are also thermally linked to the stations
with intermediate temperatures. In this fashion, the heat flowing
into the cryostat is "intercepted" at a relatively high temperature
level. The thermodynamical efficiency of a closed cycle refrigerator
is therefore excellent even when heavy cables or waveguides or the
like are used.

Progress would be still greater, of course, if it were
possible to operate the superconducting circuit itself at a higher
temperature. Although many superconductors with transition
temperatures, T_c, between $15°K$ and $18°K$ are known (12), lead
($T_c = 7.2°K$) and similar metals are predominantly used now in
electronic circuits. As discussed in Section 3, lead is also the
best contact material known. If a search for materials with satis-
factory high frequency and contact properties among the supercon-
ductors with $T_c \geq 15°K$ proves successful, the operating temperature
could be raised accordingly. This would in turn permit at least a
tenfold reduction in refrigerator input power.

6. CONCLUSION

The low power as well as the high power applications of
superconductivity are increasing. Both are expected to benefit from
the high current relay switch developed by the authors. In contrast
to previous "switching" devices, the new switch has a true "open"
position, and is thus loss free in either position. A novel method
for the storage of electrical energy is given by connecting the new
switch with a high current, high inductance superconducting solenoid.
The basic circuits are derived from analogous capacitor circuits. The
inductive energy storage is superior to the capacitive one in the
operation of pulsed light sources, for example. A sharp distinction
should be made between the cooling methods suitable for the labora-
tory and those for technical applications. For the latter, greater
use should be made of the now available closed cycle refrigerators.
Higher operating temperatures for superconducting circuits are
sought through improved materials. The development of special low
loss dielectric materials for these circuits is also suggested.

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7. ACKNOWLEDGMENT

The authors wish to thank Dr. Hans Meissner, Stevens Institute of Technology, Mr. Charles Nixon, Army Ballistic Missile Agency, Huntsville, Alabama and Mr. J. Mellichamp, Mr. M. Woodruff and Mr. L. Dathe of USAELRDL for stimulating discussions. The authors wish to express their appreciation to Mr. Lester Wilcox for fabrication of the first experimental relay switch.

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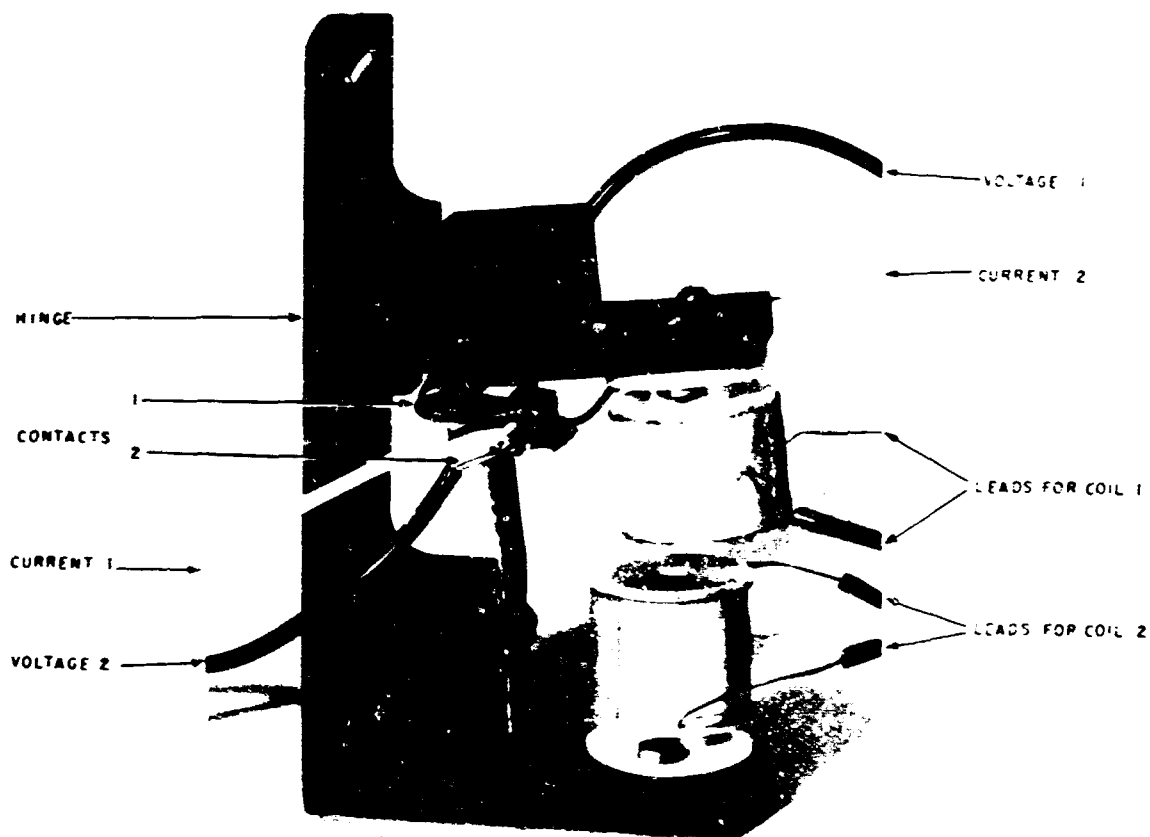
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Fig. 1

Experimental superconducting relay switch. Coils have approximately
1.6 cm diameter and 1300 turns of Mo-Re wire, 0.25 mm thick.
Critical current of contacts, $I_{cr} \approx 14$ A. Voltage leads on contacts
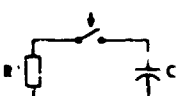are used to determine I_{cr}.

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ONE-TO-ONE CORRESPONDING ENTITIES	CORRESPONDENCE BETWEEN LEAKAGE FREE CAPACITOR AND (SUPERCONDUCTING INDUCTOR)	
QUANTIZED CHARGE (FLUX)	$Q_o = e = -1.6 \times 10^{-19}$ A SEC	$\phi_o = hc/2e = 2.1 \times 10^{-15}$ V SEC
CHARGING PROCESS	$Q = ne = \int I \, dt = UC$ C IN FARAD = A SEC/V	$\phi = n\phi_o = \int U \, dt = IL$ L IN HENRY = V SEC/A
LIMITATION OF CHARGE (FLUX)	$U < U_{MAX}$ DIELECTRIC BREAKDOWN	$I < I_{MAX}$ BREAKDOWN OF SUPERCONDUCTIVITY
TOTAL ENERGY STORED (IN JOULE=V A SEC) ENERGY STORED PER UNIT VOLUME (IN JOULE/cm^3)	$W = U^2 C/2 = UQ/2$ $w = \epsilon_o E^2/2$ $w = 0.04$ FOR $E = 10^6$ V/cm	$W = I^2 L/2 = I\phi/2$ $w = \mu_o H^2/2$ $w = 60$ FOR $H = 10^5$ A/cm
DISCHARGE THROUGH OHMIC LOAD, R', SWITCH CLOSES (OPENS) AT t=0, PRIMED QUANTITIES, U', I' REFER TO LOAD.		
FOR t < 0	$I = I' = 0$ $U = U_o = CONST.$ $U' = 0$	$U = U' = 0$ $I = I_o = CONST.$ $I' = 0$
FOR t < 0	$I = I' = -U/R' = \dot{Q} = U\dot{C}$ $U = U' = U_o \, EXP \, (-t/R'C)$	$-U = U' = -I R' = \dot{\phi} = I\dot{L}$ $I = I' = I_o \, EXP \, (-tR'/L)$

Fig. 2
Analogies between the storage of electrical charge in a hypothetical
leakage free capacitor (center) and the storage of magnetic flux in
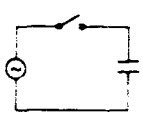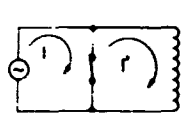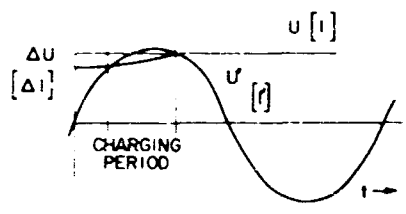a superconducting inductor (right).

CORRESPONDING ENTITIES	LEAKAGE FREE CAPACITOR	SUPERCONDUCTING INDUCTOR
BASIC AC CHARGING CIRCUIT, WITH CONSTANT VOLTAGE (CONSTANT CURRENT) SOURCE.		
CHARGING PERIOD BEGINS, SWITCH CLOSES (OPENS) WHEN	$U' = U + \delta U$	$I' = I + \delta I$
DURING CHARGING PERIOD	$I = I' > 0$	$U = U' > 0$
CHARGING PERIOD ENDED, SWITCH OPENED (CLOSED) WHEN	$I = I' = 0$	$U = U' = 0$

Fig. 3
Corresponding a.c. charging circuits, as in Fig. 2.

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CHARGING CIRCUIT SIMILAR TO ABOVE, BUT WITH AUXILIARY TRANSFORMER Tr. WINDING W2 IS SUPERCONDUCTING.

THIS CIRCUIT CAN ALSO BE USED FOR DISCHARGE, WHEN CONNECTED TO RESONANT LOAD CIRCUIT

CIRCUIT WITH REVERSAL SWITCH. EQUIVALENT TO VIBRATOR CIRCUIT WITH CAPACITORS.

W2 IS SUPERCONDUCTING AND STORES CURRENT I', FLUX I'L'. UPON REVERSAL AND OPENING OF S3, FLUX IN Tr CHANGES TO I'L', PRODUCING VOLTAGE IN W1

SWITCHING SEQUENCE FOR DISCHARGE SEQUENCE FOR CHARGING ANALOGOUS SEQUENCE ALTERNATES WITH S2 IN POSITION 'a' AND S2 IN POSITION 'b'
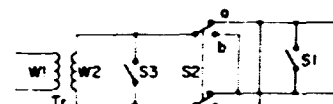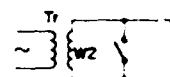
	S1	S2	S3
STANDBY a	1	0	a
DISCHARGE	0	U	a
	1	1	a
REVERSAL	1	1	b
STANDBY b	1	0	b
CONTINUED AS ABOVE			b

Fig. 4 Charging circuits for superconducting solenoids using super-conducting switches and transformers. Primary transformer winding (W 1) couples through wall of cryostat. Heavy current leads into the cryostat are thus unnecessary.

EMERGENCY TRANSMITTER FOR HIGH POWER PULSES.

LOSSLESS STORAGE IS PROVIDED BY SHUNTING THE SUPERCONDUCTING INDUCTOR L WITH SUPERCONDUCTING SWITCH S. IN THE STANDBY POSITION CURRENT IS TRANSFERRED OUT OF THE CRYOSTAT AND GOES THROUGH SWITCHING TRANSISTOR T1 WITH $R \approx 10^{-3}$ OHMS FOR THE EFFECTIVE RESISTANCE OF T1. DECAY IN THE STANDBY POSITION IS DESCRIBED BY A TIME CONSTANT $\tau = L/R \ 10^4 \ 10^6$ SEC

OSCILLATION THROUGH OPENING AND CLOSING OF T1 AND T2 WITH RESONANCE FREQUENCY IN CONVENTIONAL MANNER
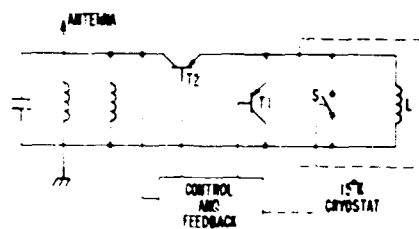
	S	T1	T2
LOSSLESS STORAGE	1	1	0
STANDBY	0	1	0
START OF OSCILLATION	0	0	1
OSCILLATION WITH RESONANCE FREQUENCY T1,T2 CONTROLLED BY FEEDBACK NETWORK	0	1	0
	1	0	1
	0	1	0
LOSSLESS STORAGE	1	1	0

Fig. 5 Example of potential future application of energy storage in superconducting solenoid. Lossless storage is given with super-conducting switch S. Energy is lost only during the standby and operative periods, when solenoid current is controlled by switching transistors T 1 and T 2.

PULSED AND/OR
MODULATED LIGHT SOURCE.
USING SUPERCONDUCTING
INDUCTOR L AS CONSTANT
CURRENT HIGH POWER
SOURCE.

PULSED LIGHT
SOURCE (INJECTION
LASER. XENON
LAMP ETC.)

T2

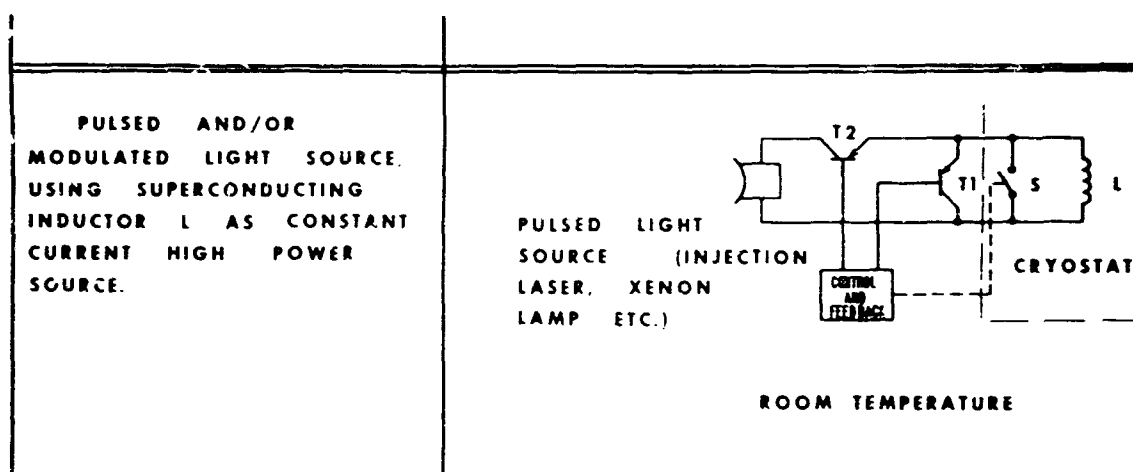T1 S L

CONTROL
AND
FEEDBACK

CRYOSTAT

ROOM TEMPERATURE

Fig. 6

Operation of pulsed light source from superconducting solenoid,
similar to Fig. 4. In contrast to a capacitor bank, a super-
conducting solenoid is essentially a constant current source which
is more suitable for many pulsed light sources.